Presentation for the Global Solar and Wind Resource Assessment Project

Wind Resource Assessment and Mapping at the U.S. National Renewable Energy Laboratory

Dennis Elliott
NREL, Principal Scientist

Outline of Presentation

- Introduction and rationale for wind mapping
- UNEP wind mapping project activities
- Examples of NREL's high-resolution wind maps
  - Developing country - Philippines Atlas
  - Wind Powering America - North Dakota
- NREL's GIS-based wind mapping system
  - Logic of mapping system and required inputs
  - Data sets and analysis procedures
  - Outputs of mapping system
- Conclusions

Rationale for Wind Resource Assessment and Mapping

The lack of reliable and detailed wind energy resource maps and data is a significant impediment to large-scale use of wind energy technologies, particularly in the developing world.

UNEP Project Activities for High-Resolution (1-km) Wind Mapping

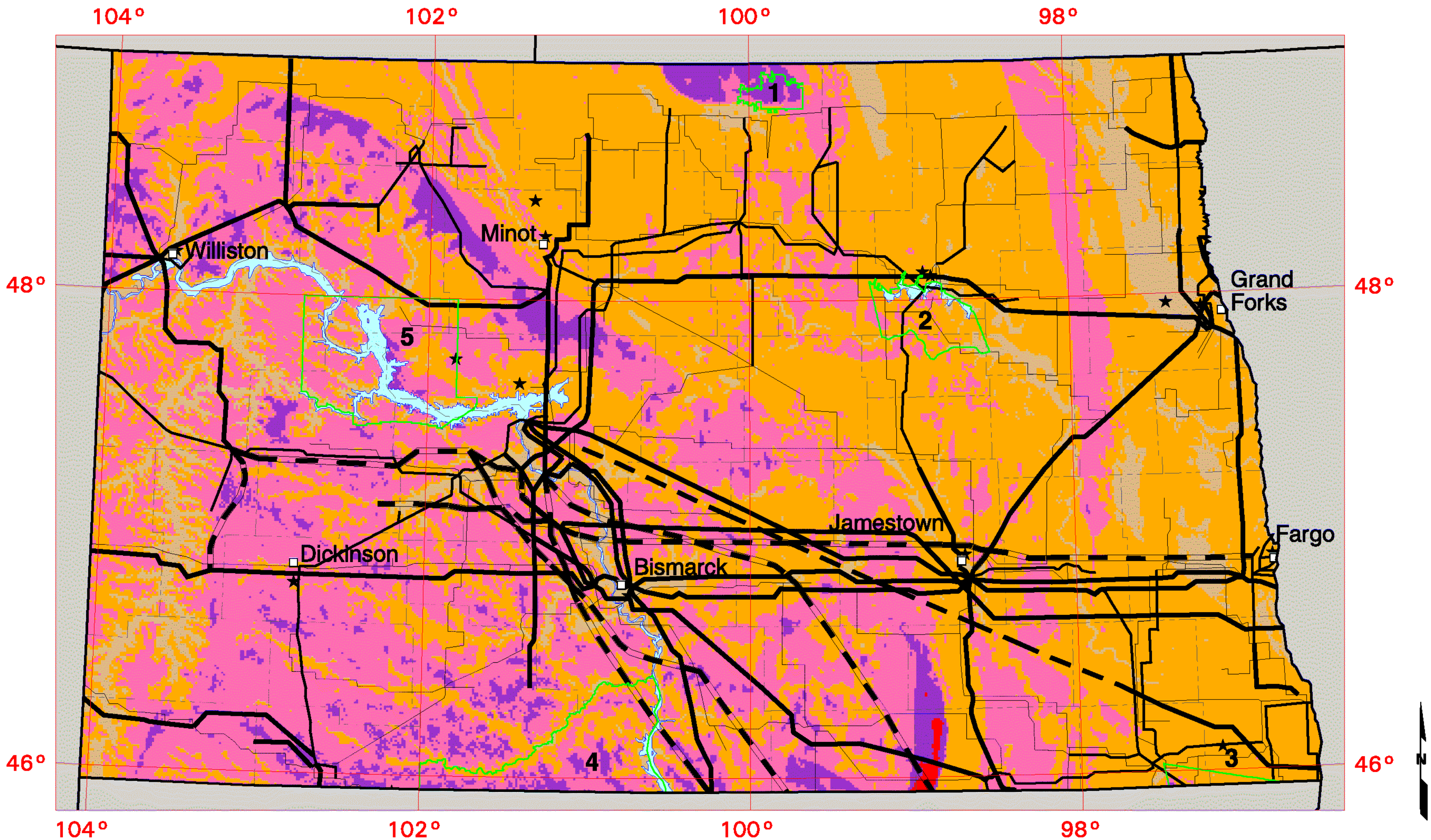
- Review previous surveys
- Identify and obtain existing wind and other meteorological data
  - NREL's global database
  - Host country data
- Process and analyze data
- Develop wind resource maps and other products using NREL's GIS-based mapping system
- Produce wind resource atlas

UNEP Project Deliverables for Regional Wind Mapping

- High resolution (1-km) wind maps, elevation maps, and political maps
- Wind resource atlas with maps and summaries of salient wind characteristics (e.g. seasonal/monthly, diurnal, interannual, direction frequency, etc.)
- Maps and atlas on CD-ROM

NREL's State-of-the-art High Resolution (1km) Wind Resource Maps

North Dakota - Wind Resource Map



Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7

[a] Wind speeds are based on a Weibull k value of 2.0

★ Meteorological Station with Wind Data
□ City or Town

40 0 40 80 120 160 Kilometers
25 0 25 50 75 100 Miles

Transmission Line Voltage

- 69 Kilovolts
- 115 Kilovolts
- 230 Kilovolts
- 345 Kilovolts
- Under Construction

Indian Reservations

1. Turtle Mountain
2. Devil's Lake Sioux
3. Lake Traverse
4. Standing Rock
5. Fort Berthold

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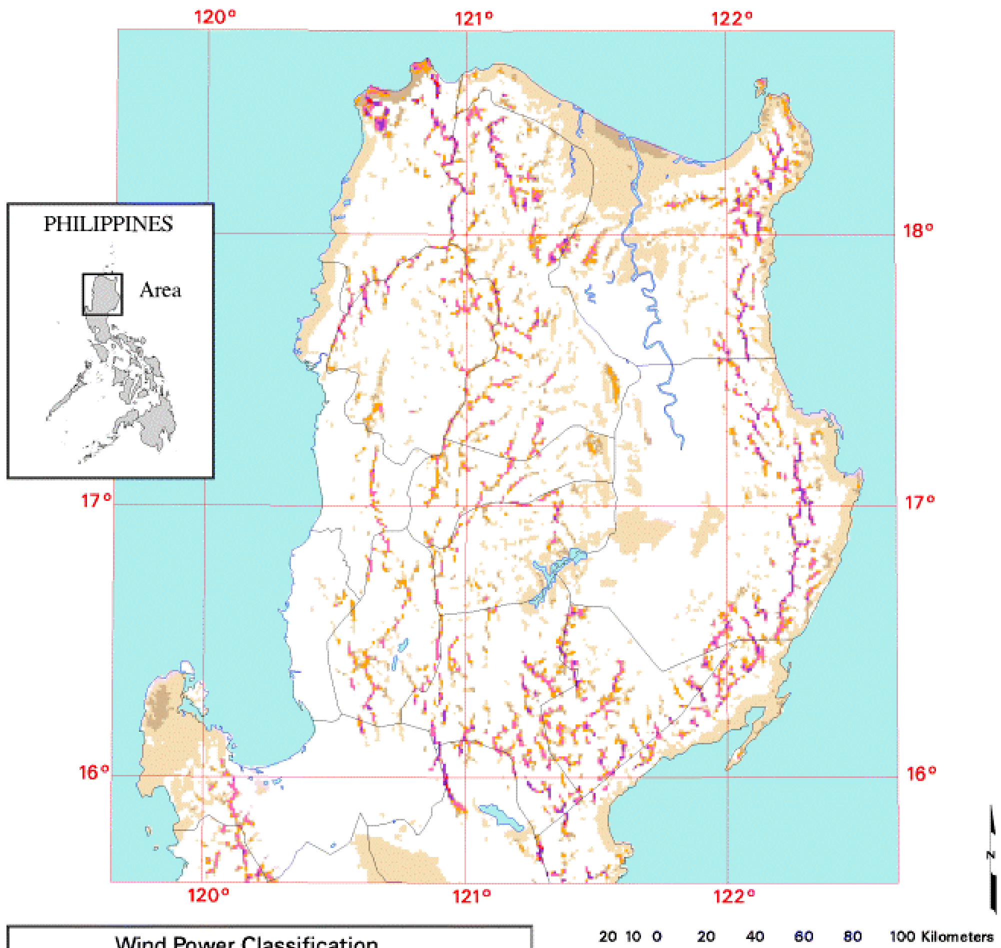
National Renewable Energy Laboratory

Philippines - Northern Luzon
Most Favorable Wind Resource Areas



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Good	Excellent	300 - 400	6.4 - 7.0
Excellent		400 - 600	7.0 - 8.0
		600 - 800	8.0 - 8.8
		800 - 1200	8.8 - 10.1

[a] Wind speeds are based on a Weibull k value of 2.0

The wind resource classification is specific for both utility scale and rural applications and applies to areas with low surface roughness.

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NREL contacts:
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Marc Schwartz

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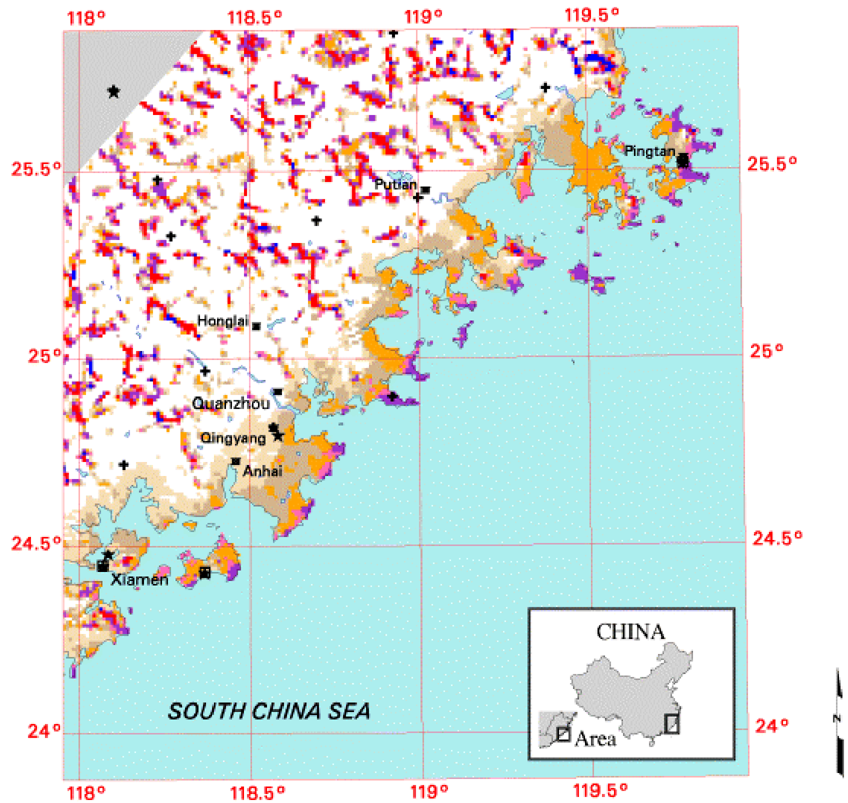
Southeast China - Central Coast of Fujian
Map of Favorable Wind Resource Areas



20 10 0 20 40 60 Kilometers

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Fair	100 - 200	4.4 - 5.6
Moderate	200 - 300	5.6 - 6.4
Good	300 - 400	6.4 - 7.0
Excellent	400 - 500	7.0 - 7.5
	500 - 700	7.5 - 8.4
	700 - 1000	8.4 - 9.6
	> 1000	> 9.6

[a] Wind speeds are based on a Weibull k value of 2.0 estimated for many coastal areas of SE China.

★ GTS Surface Meteorological Station
□ GTS Upper-Air Meteorological Station
✚ Additional Surface Meteorological Station
■ City

The wind resource classification is for utility scale applications and applies to areas with low surface roughness. The Global Telecommunications System (GTS) meteorological stations are part of NREL's global database. The data for the additional meteorological stations were provided by the State Power Company of China.

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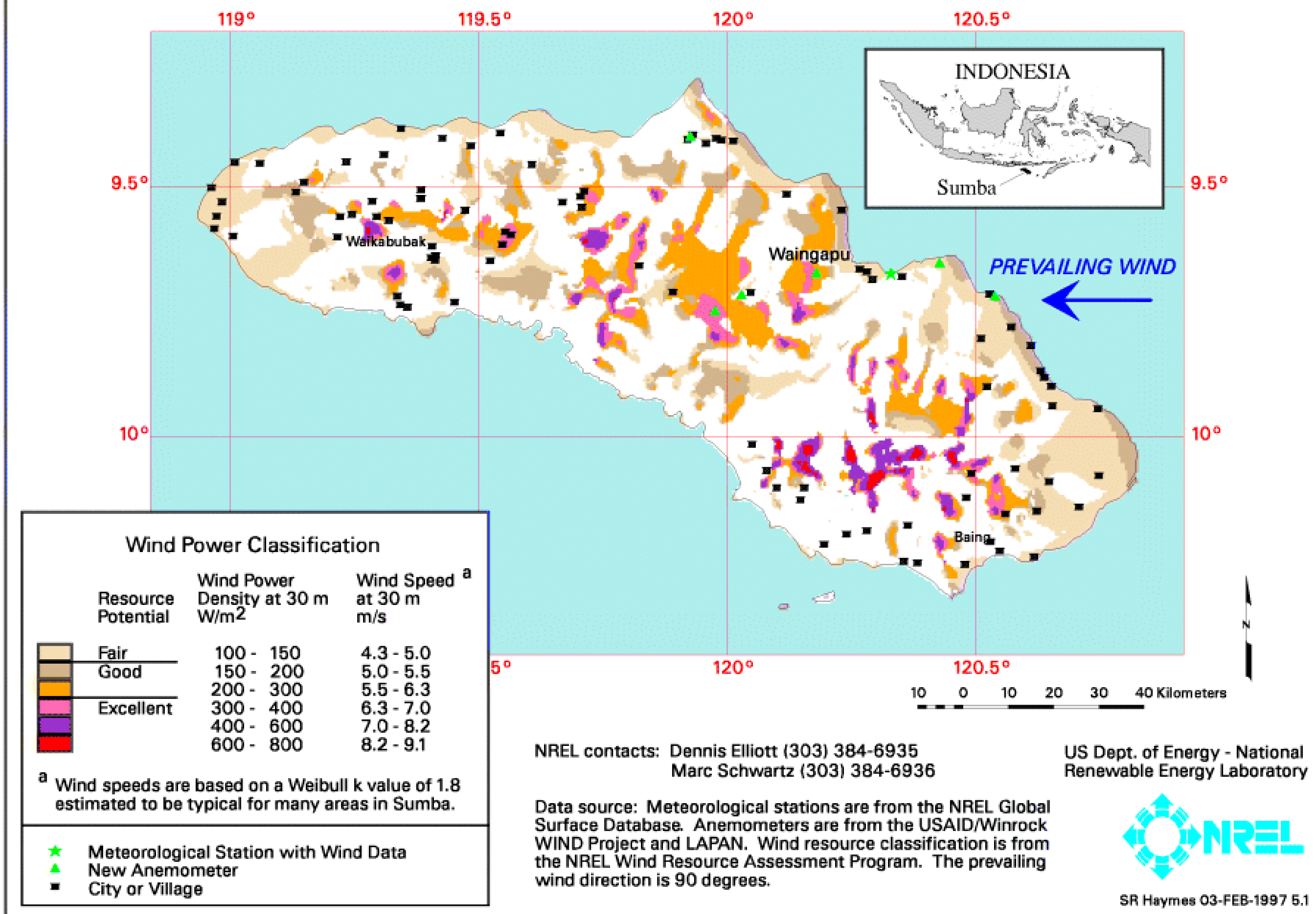
Sumba, Indonesia - Favorable Wind Resource Areas

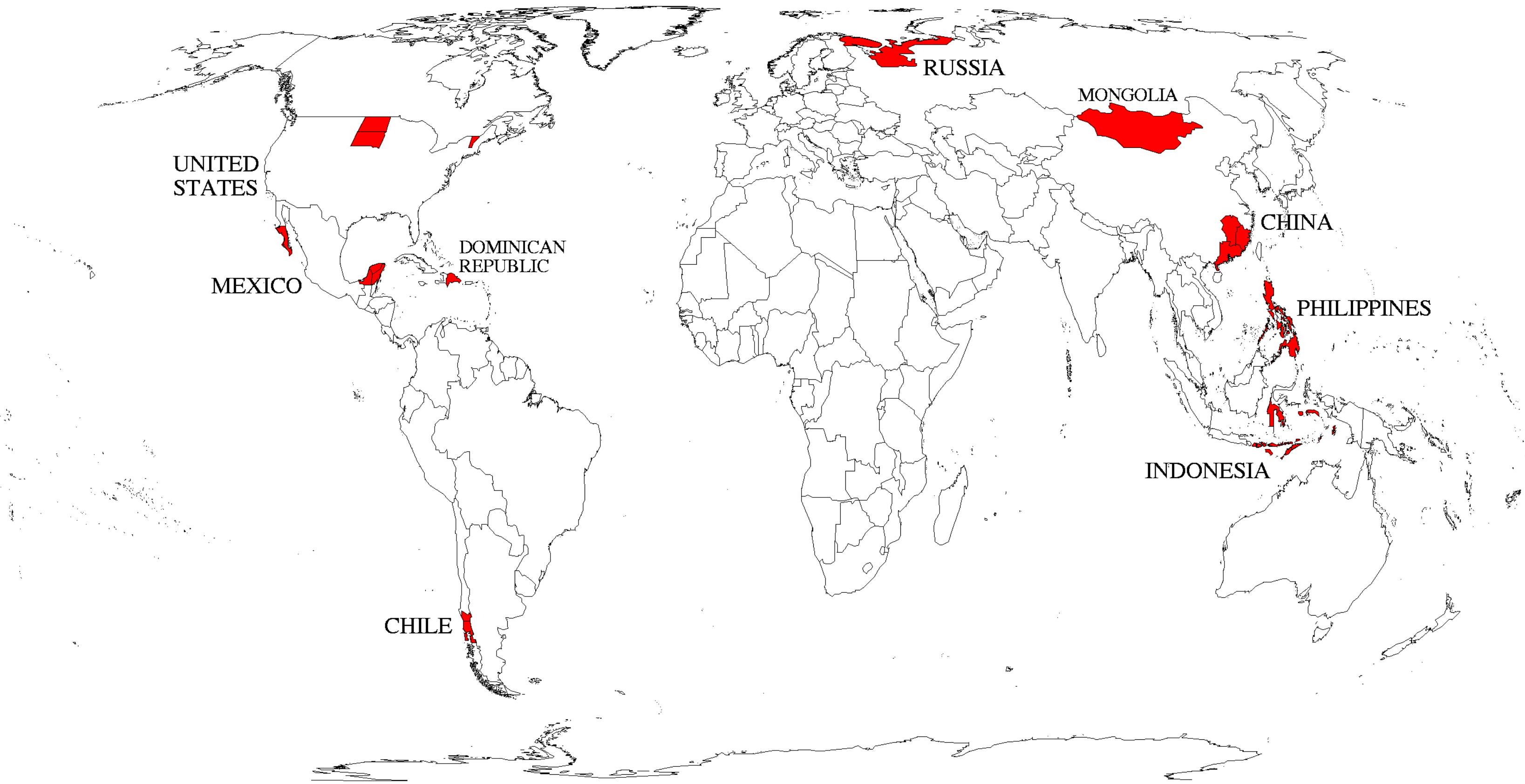


Applications of NREL's Wind Mapping System

Used to produce high-resolution (1km^2) regional or national wind resource maps

- United States - Dakotas, Vermont
- Mexico - Baja California Sur, Yucatan Peninsula
- Chile - Regions IX and X (Central Chile)
- Indonesia - Southeastern islands
- China - Southeastern areas
- Philippines - entire country
- Dominican Republic - entire country
- Mongolia - entire country

NREL Wind Resource Mapping Projects Since 1996



The project areas are shown to the provincial or state level and may not represent the true extent of the actual wind maps. All of the maps including the high resolution (1 km) wind resource maps are developed with NREL's GIS-based mapping system.

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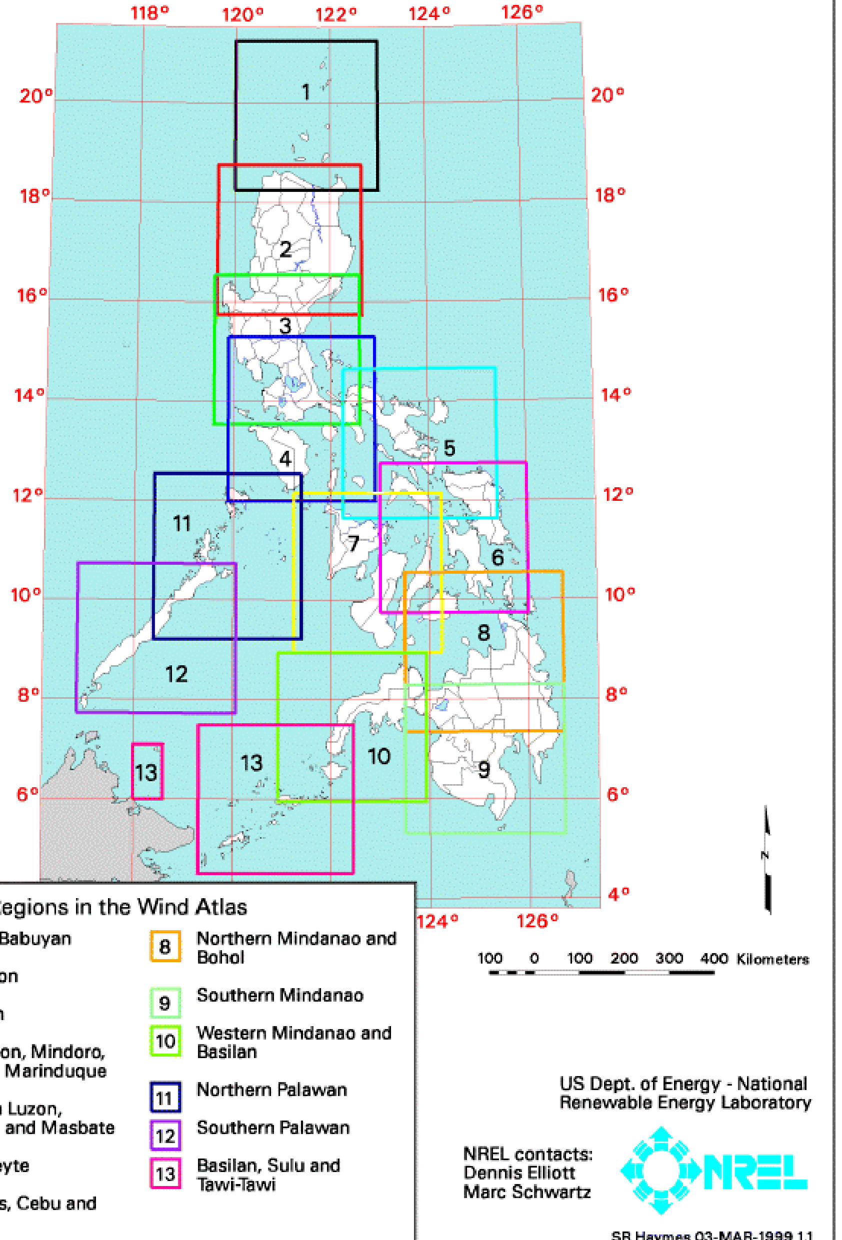
NREL

08-MAR-2000 3.4

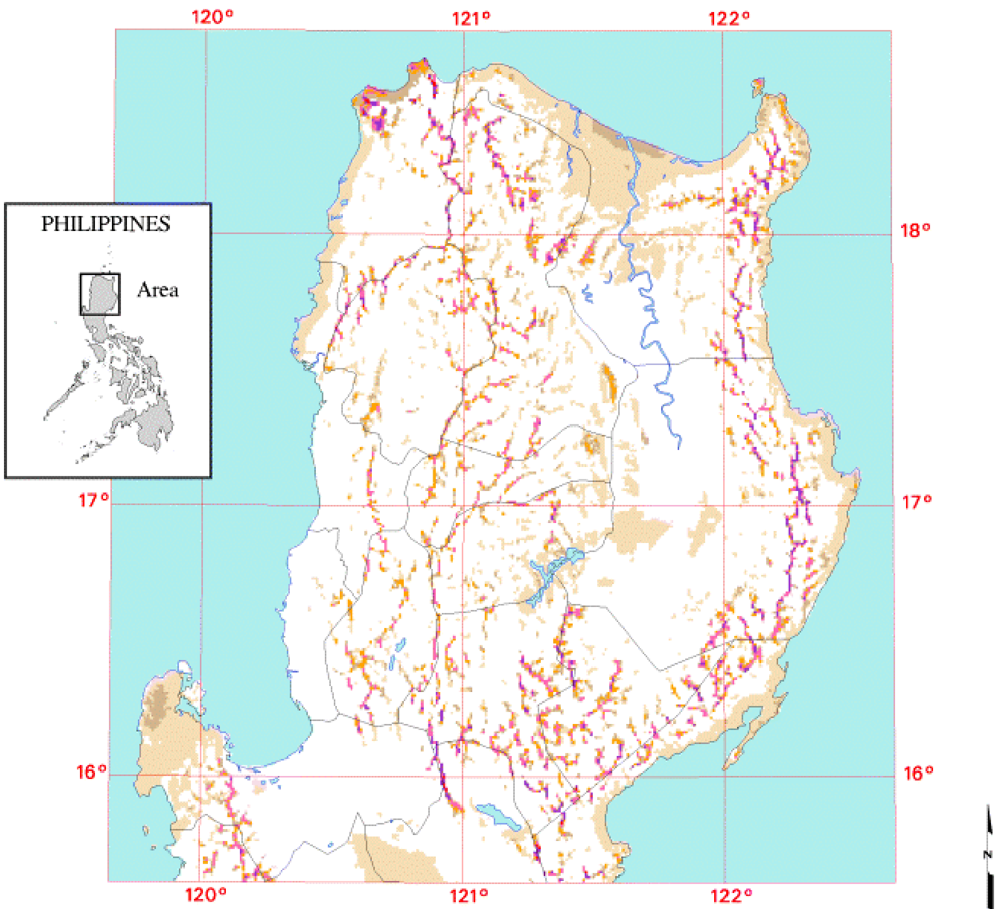
Product Examples
Developing Country
Philippines Wind Atlas

Wind Energy Resource Atlas of the Philippines
Contents

Philippines
Key to the Regions in the Wind Atlas



Philippines - Northern Luzon
Most Favorable Wind Resource Areas



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[a] Wind speeds are based on a Weibull k value of 2.0

The wind resource classification is specific for both utility scale and rural applications and applies to areas with low surface roughness.

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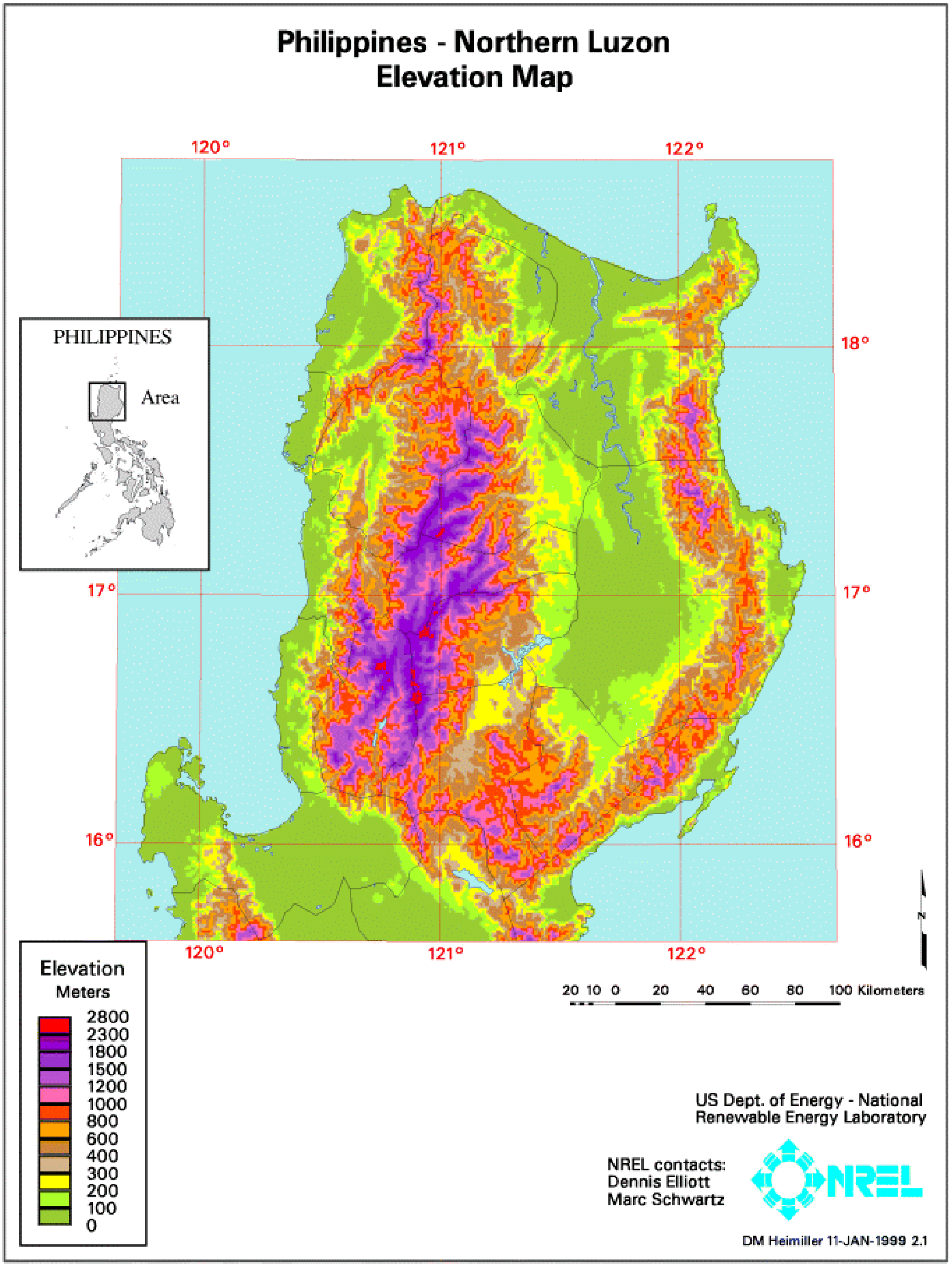
Philippines - Northern Luzon
Elevation Map
120°
121°
122°
18°
17°
16°
PHILIPPINES
Area
Elevation
Meters
2800
2300
1800
1500
1200
1000
800
600
400
300
200
100
0
20 10 0 20 40 60 80 100 Kilometers
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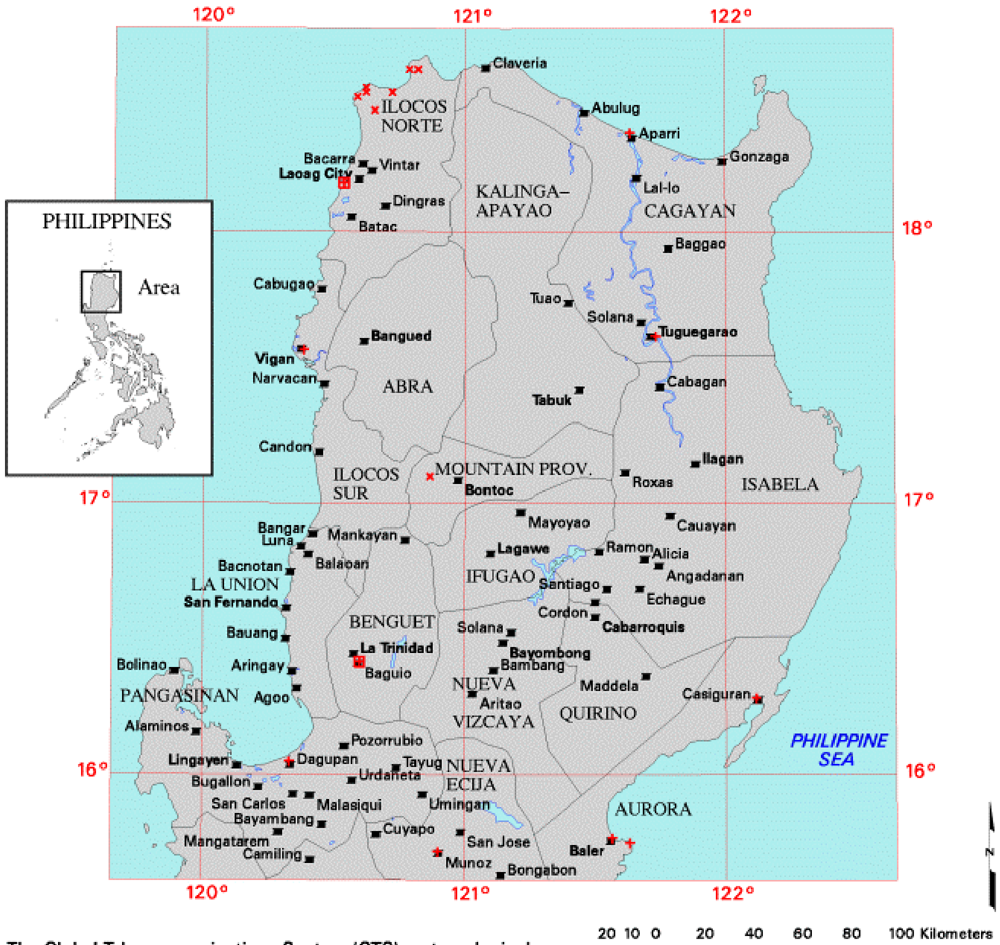
DM Heimiller 11-JAN-1999 2.1

Philippines - Northern Luzon
Political Base Map



The Global Telecommunications System (GTS) meteorological stations are part of NREL's global database. Additional data for many of the meteorological stations were provided by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). The data for the wind monitoring sites were provided by the Philippine National Power Corporation (NPC).

Legend

- + GTS Surface Meteorological Station with Wind Data
- □ GTS Upper-Air Meteorological Station
- × NPC Wind Measurement Site
- City or **Provincial Capital**

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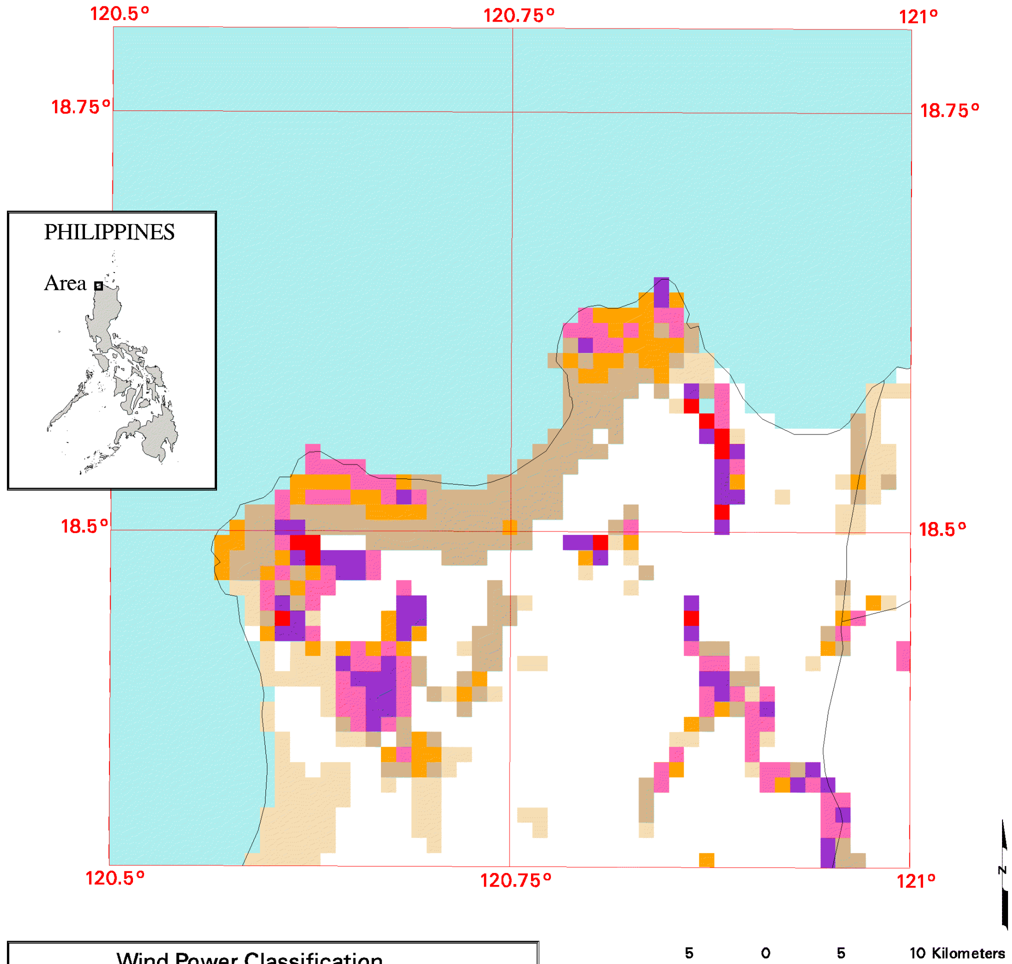
Philippines - Northwest Tip of Luzon
Most Favorable Wind Resource Areas



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PHILIPPINES - WIND ELECTRIC POTENTIAL

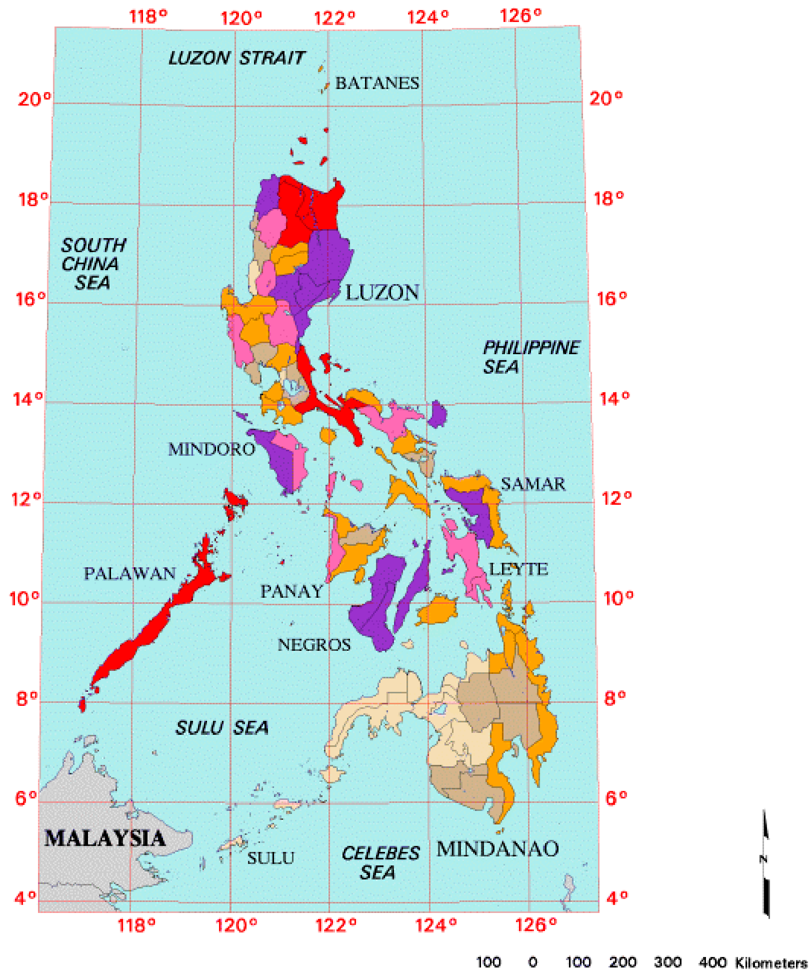
Good-to-Excellent Wind Resource at 30 m (Utility Scale)

Wind Resource Utility Scale	Wind Power W/m2	Wind Speed m/s	Total Area km^2	Total Capacity Installed MW	Total Power GWh/yr
Good	300-400	6.4-7.0	5,541	38,400	85,400
Excellent	400-500	7.0-8.0	2,841	19,700	52,200
Excellent	500-700	8.0-8.8	2,258	15,600	47,900
Excellent	700-1250	8.8-10.1	415	2,900	9,700
Total			11,055	76,600	195,200

Assumptions
Turbine Size – 500 kW
Hub Height – 40m
Rotor Diameter – 38m
Turbine Spacing – 10D by 5D
Capacity/km^2 – 6.9 MW

Philippines - Wind Electric Potential

Good-to-Excellent Wind Resource (Utility Scale Classification)



Philippines Total - 76,600 MW

Wind Electric Potential
Megawatts

- < 100
- 100 - 500
- 500 - 1,000
- 1,000 - 2,000
- 2,000 - 3,000
- 3,000 - 5,200

The following assumptions were used in calculating the total potential wind electric capacity installed:

Minimum wind power - 300 W/m2
Turbine size - 500 kW
Hub height - 40 m
Rotor diameter - 38 m
5D Side-to-side spacing - 190 m
10D Front-to-back spacing - 380 m
Swept area - 1134 m2
Turbines/km2 - 13.9
Capacity/km2 - 6.9 MW

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NREL contacts:
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Marc Schwartz

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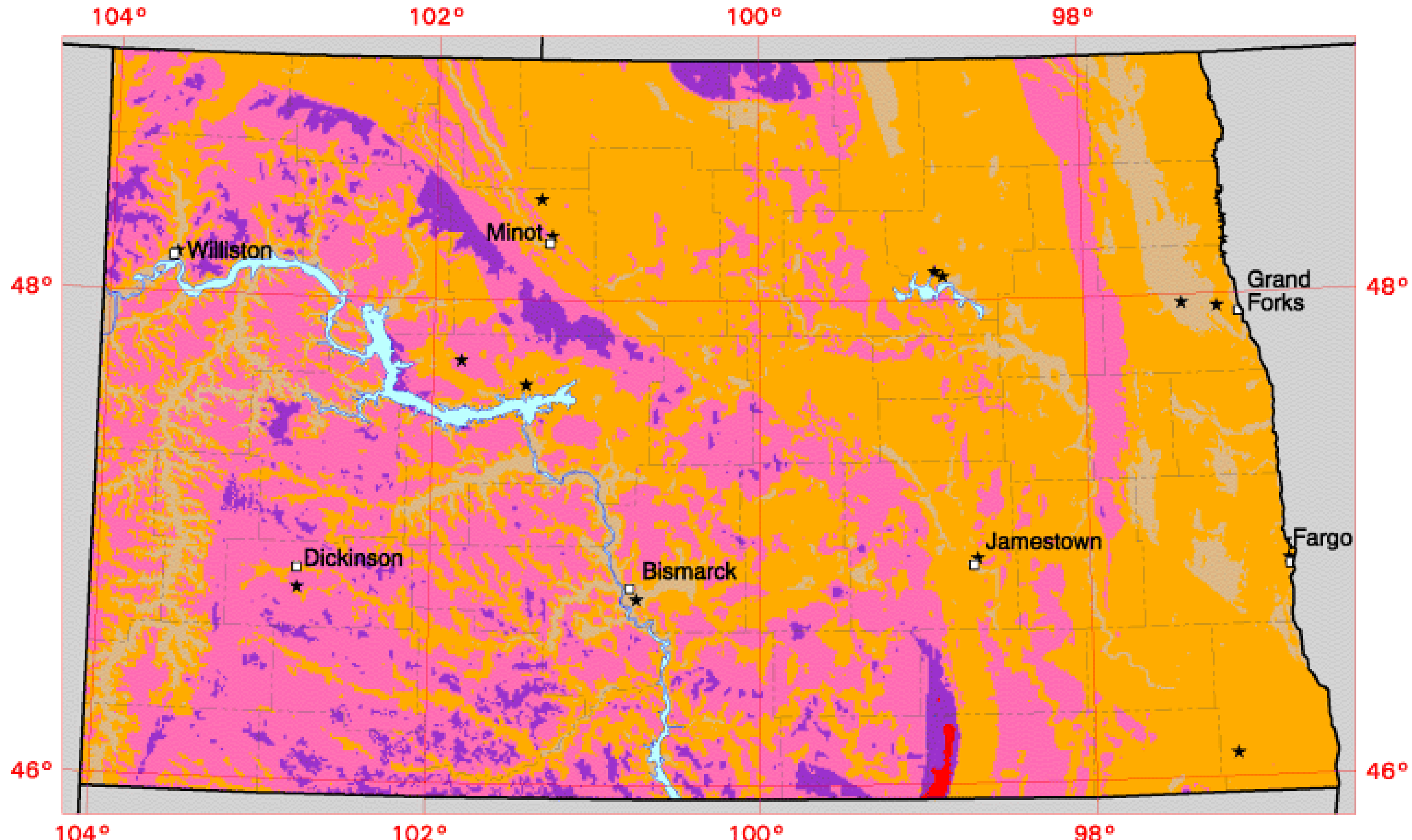
Product Examples
Wind Powering America
North Dakota

North Dakota - Wind Resource Map



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N

★ Meteorological Station with Wind Data

■ City or Town

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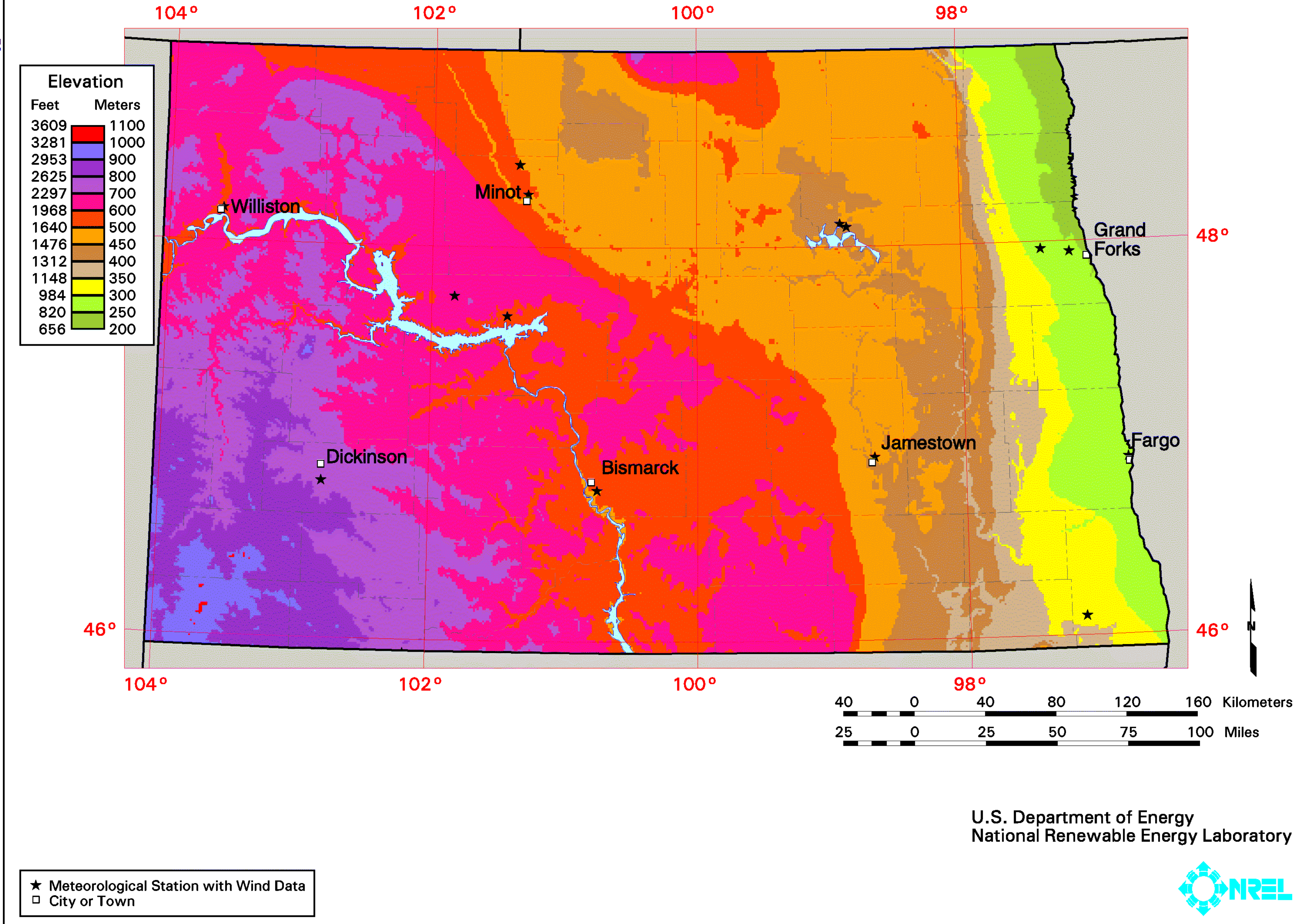
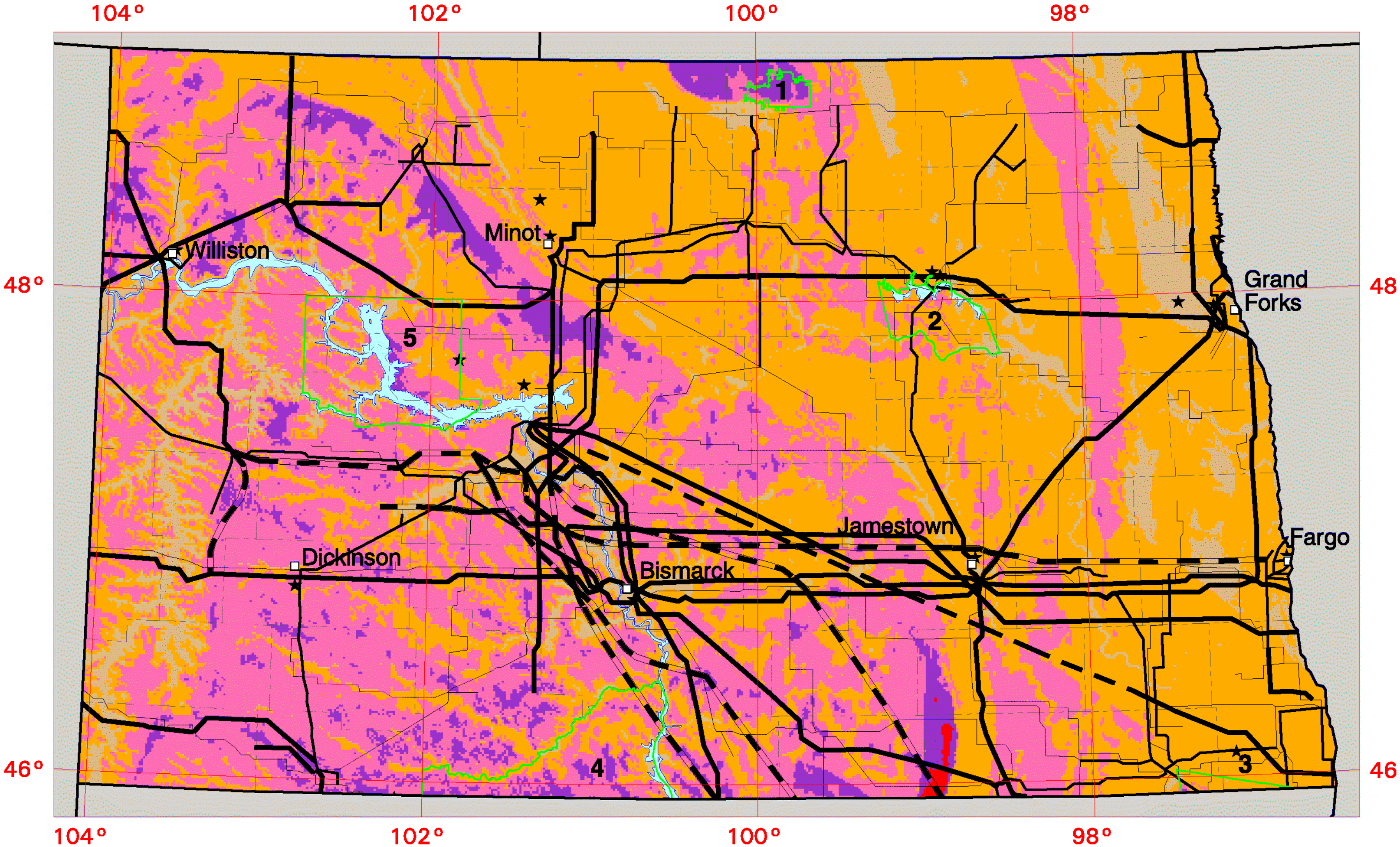
North Dakota - Elevation Map



North Dakota - Wind Resource Map



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N

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- Under Construction

Indian Reservations

1. Turtle Mountain
2. Devil's Lake Sioux
3. Lake Traverse
4. Standing Rock
5. Fort Berthold

U.S. Department of Energy
National Renewable Energy Laboratory

NREL's GIS-based Wind Mapping System

NREL's Wind Mapping System

- Computerized mapping system started in 1995
- Uses Geographical Information System (GIS) software (ArcInfo® and ArcView®)
- Designed for regional wind mapping (not micrositing)
- Empirical and analytical approach
- Does not depend on high quality surface wind observations
- Model inputs - formatted meteorological data and digital terrain data

Logic of Mapping System

- Model Design
  - ARC/INFO® GIS-based
    - 31 custom programs
    - Over 16,000 lines of code
  - Modules for physiographic settings
    - Inland
    - Coastal and Islands
    - Lake shores
  - Modules for terrain settings
    - Complex - mountainous terrain
    - Flat - includes sloping terrain and minor relief
    - Mixed - a combination of complex and flat terrain
  - Appropriate modules are applied
  - Model domain larger than mapping domain

Logic of Mapping System

- Inputs for computerized wind mapping
  - Meteorological Data
    - Vertical profile of wind power
    - Near surface wind power for coastal/ocean areas
    - Wind power rose (percent of power by direction)
  - Digital Geographic Data
    - Terrain - 1km^2 elevation data
    - Coastline and hydrography
  - Geographic zones for meteorological data

Data Collection for Model Inputs

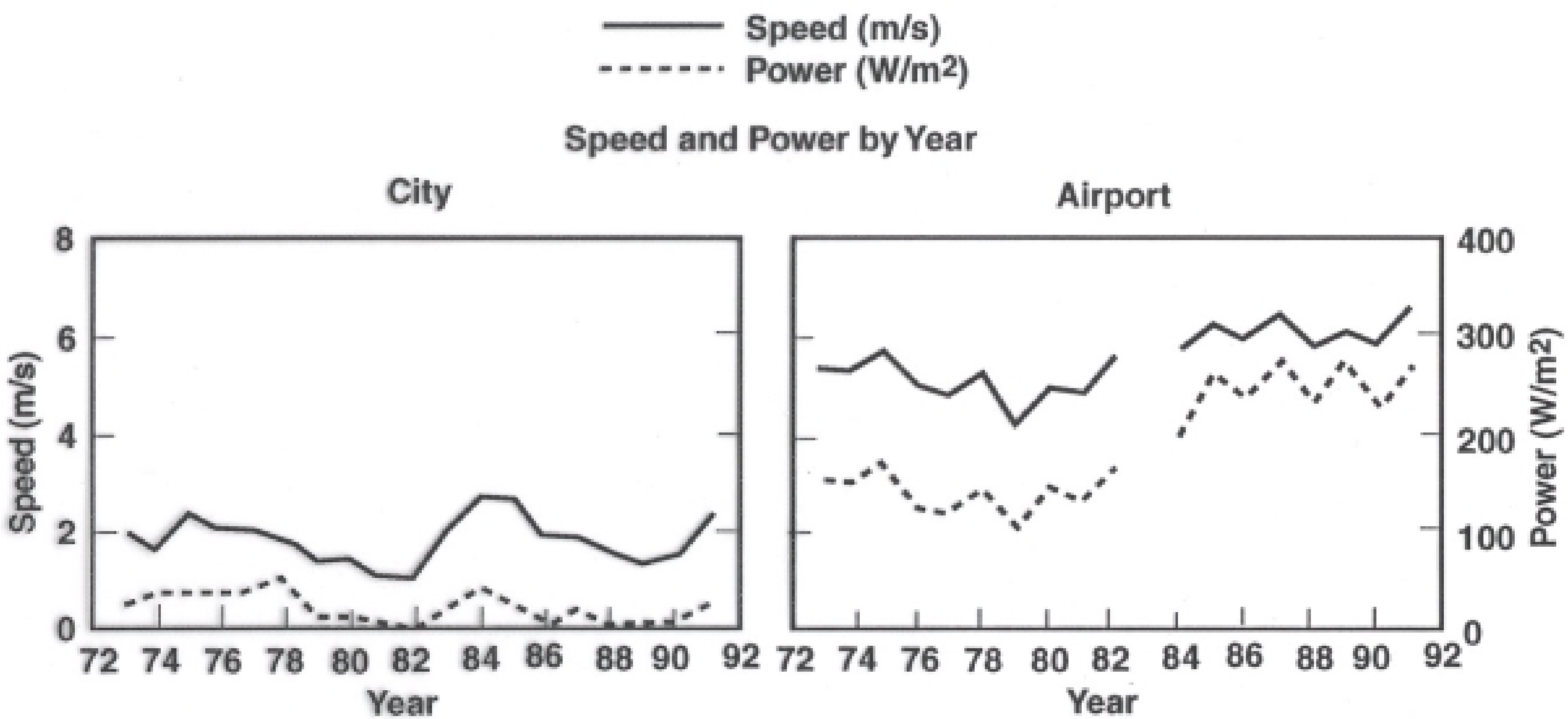
- NREL’s global meteorological data set
  - surface station data
  - upper-air data
  - ocean data (satellite, ship)
- Host-country meteorological service wind summaries and reports
- Other wind measurement data available from host country
- NREL’s global terrain and geographic data

Major Global Data Sets used by NREL for Wind Resource Assessment

Data Set	Type of Information	Source	Period of Record
Surface Station Data	Surface observations at 20000 stations	NOAA/NCDC	1973-1998
Upper Air Station Data	Rawinsonde and pibal observations at 1800 stations	NCAR	1973-1998
Satellite-derived Ocean Wind Data	10-m ocean wind speeds gridded to 0.25 deg	NASA/JPL	1988-1998
Marine Climatic Atlas of the World	Gridded (1.0 deg) statistics of historical ship wind observations	NOAA/NCDC	1854-1969
Reanalysis Upper Air Data	Model-derived gridded (~200km) upper air data	NCAR	1958-1997
Global Upper Air Climatic Atlas	Model-derived gridded (2.5 deg) upper air statistics	NOAA/NCDC	1980-1991
Digital Geographic Data	Political, hydrography, etc.	ESRI	
Digital Terrain Data	Elevation – 1 km resolution	USGS/EROS	

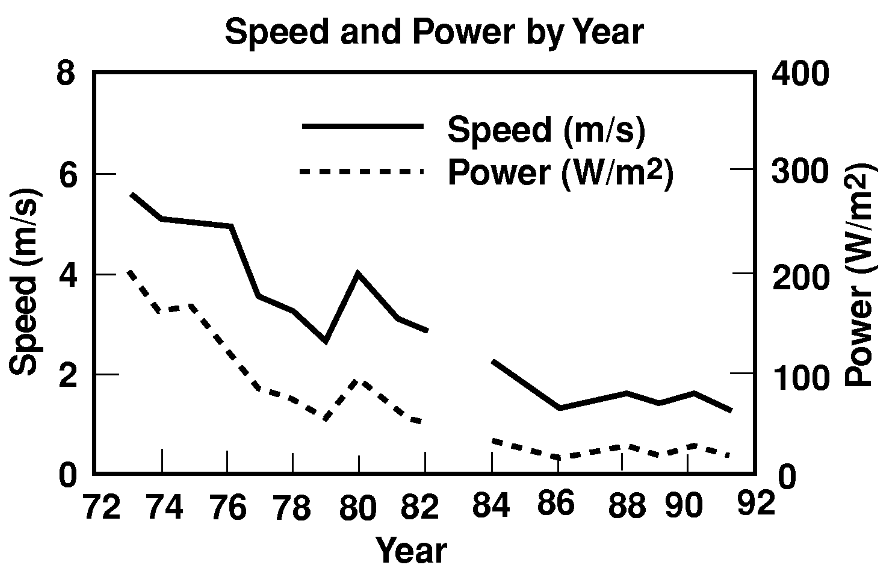
NREL's Quality Assessment of Meteorological Data

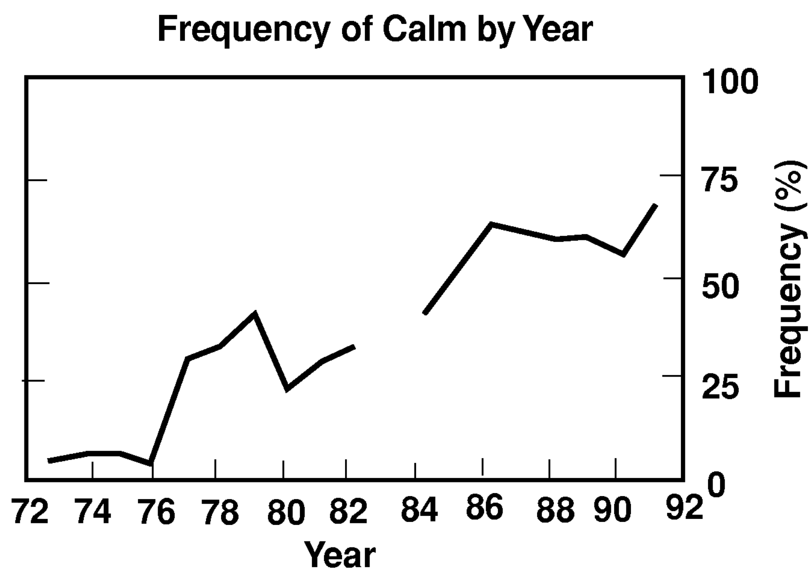
Chetumal, Mexico
Yucatan Peninsula - East Coast



	Period	Speed (m/s)	Power (W/m^2)
City	1973-91	1.9	22
Airport	1984-91	6.1	245

Mexicali Airport, Mexico
Baja California



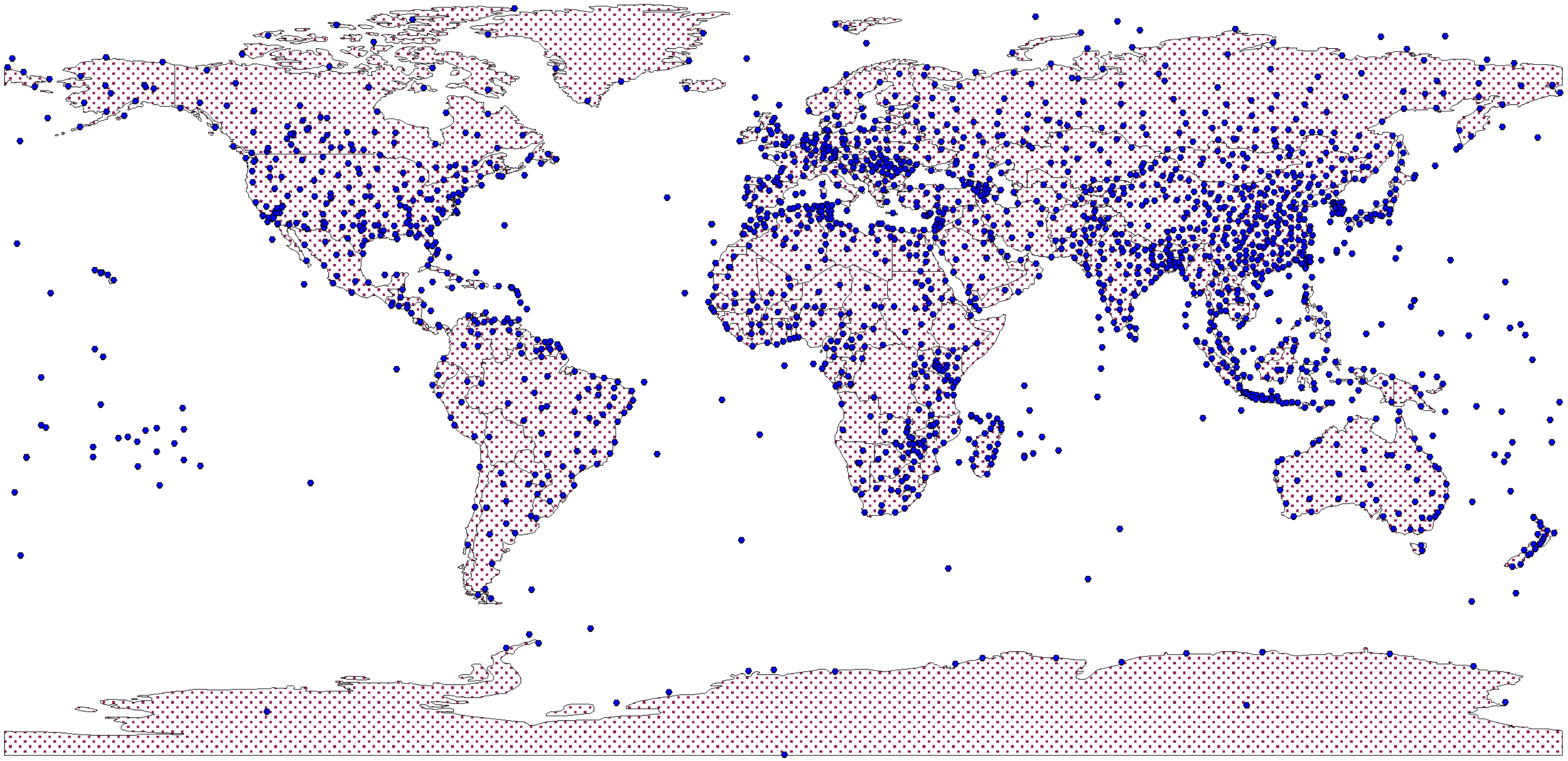


Period	Wind Speed (m/s)	Power (W/m^2)	Calm (%)
1973-75	5.2	170	7
1986-91	1.5	20	62

Comparison of Wind Power Densities for Selected Areas in Mexico

Region	Location	Wind Power Density (W/m^2): OLADE Atlas (1983)	Wind Power Density (W/m^2): NREL Analysis (1995)
Yucatan Peninsula	Merida	22	165
	Campeche	23	120
	Chetumal	28	205
Northern Gulf Plain	Tampico	8	205
	Ciudad Victoria	32	170
	Matamoros	32	165
Central Highlands	Durango	8	140
	San Luis Potosi	35	155
	Zacatecas	94	270
Northwest	Chihuahua	27	120
	Hermosillo	3	80
	La Paz	10	85

Worldwide Weather Balloon Launch Sites



Logic of Mapping System (cont.)

- Meteorological data, digital geographic data, and GIS software combined in wind power calculation modules
- Uses “top down” method to adjust free-air winds for estimating base wind power density values
- Base wind power density values are adjusted by terrain and stability factors in model

Output of Mapping System

- Final products
  - wind power density maps (1 km^2 resolution)
  - topographic maps (1 km^2 resolution)
  - political and other types of maps
- Estimates of wind power density displayed for most favorable areas, considering:
  - level of wind resource
  - exposure to prevailing winds
  - terrain slope

Conclusions

- Cursory methods in many previous surveys underestimate wind potential
- Comprehensive approach and various types of data are used to develop reliable assessments
- Many areas of good wind potential have been identified that were previously estimated to have inadequate potential
- Advanced GIS modeling of wind resource results in more sophisticated, detailed and consistent analysis
- Reliable wind resource maps identify optimum locations for measurement programs and facilitate project decisions

Appendices

Wind Resource Assessment and Mapping at NREL

NREL's Wind Resource Assessment Group

Dennis Elliott (team leader)

Marc Schwartz

George Scott

Steve Haymes

Donna Heimiller

Ray George

Basic Principles of Wind Resource Estimation

WIND POWER RELATIONSHIPS

$$P = \tfrac{1}{2}\,\rho\,A\,V^3$$

- P: AVAILABLE POWER
- ρ: AIR DENSITY
- A: SWEPT AREA
- V^3: WIND VELOCITY CUBED

EXAMPLE: SAME TURBINE, SEA LEVEL, DIFFERENT SITE

$$P = KV^3$$

WIND VELOCITY = v $\quad P_1 = Kv^3$

WIND VELOCITY = $2v$ $\quad P_2 = 8Kv^3$

$$P_2 = 8P_1$$

EXAMPLE: DIFFERENT TURBINE, SEA LEVEL, SAME SITE

$$P = CD^2$$

ROTOR DIAMETER = d $\quad P_1 = Cd^2$

ROTOR DIAMETER = $2d$ $\quad P_2 = 4Cd^2$

$$P_2 = 4P_1$$

Comparison of Annual Average Wind Power at Four Sites with Identical Annual Average Wind Speeds at 10 m

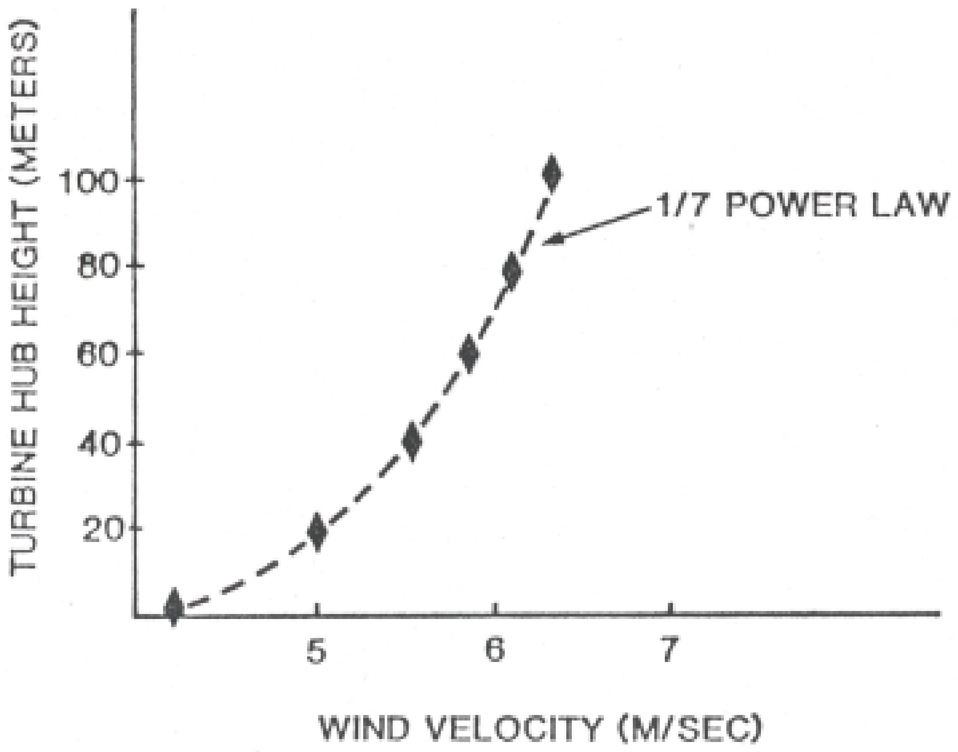
Site	Annual Average Wind Speed, m/s (mph)	Annual Average Wind Power Density, W/m²	Wind Power Power Class
Constant Wind Speed (hypothetical)	6.3 (14)	150	2-3
Culebra, Puerto Rico	6.3 (14)	220	4
Tiana Beach, New York	6.3 (14)	285	5
San Gorgonio, California	6.3 (14)	365	6

S9106046.5

WIND VELOCITY VERSUS ALTITUDE

$$\frac{V}{V_o} = \left(\frac{H}{H_o}\right)^n$$

WHERE: V_o = REFERENCE WIND VELOCITY
H_o = REFERENCE HEIGHT
n = DEPENDENT EXPONENT



History of Wind Mapping in DOE's Wind Program

Late 1970s - 1980s

- **Maps produced by subjective analysis and interpolation**
- **Reliable surface data key to quality of results**
- **Examples: US atlas, global map**

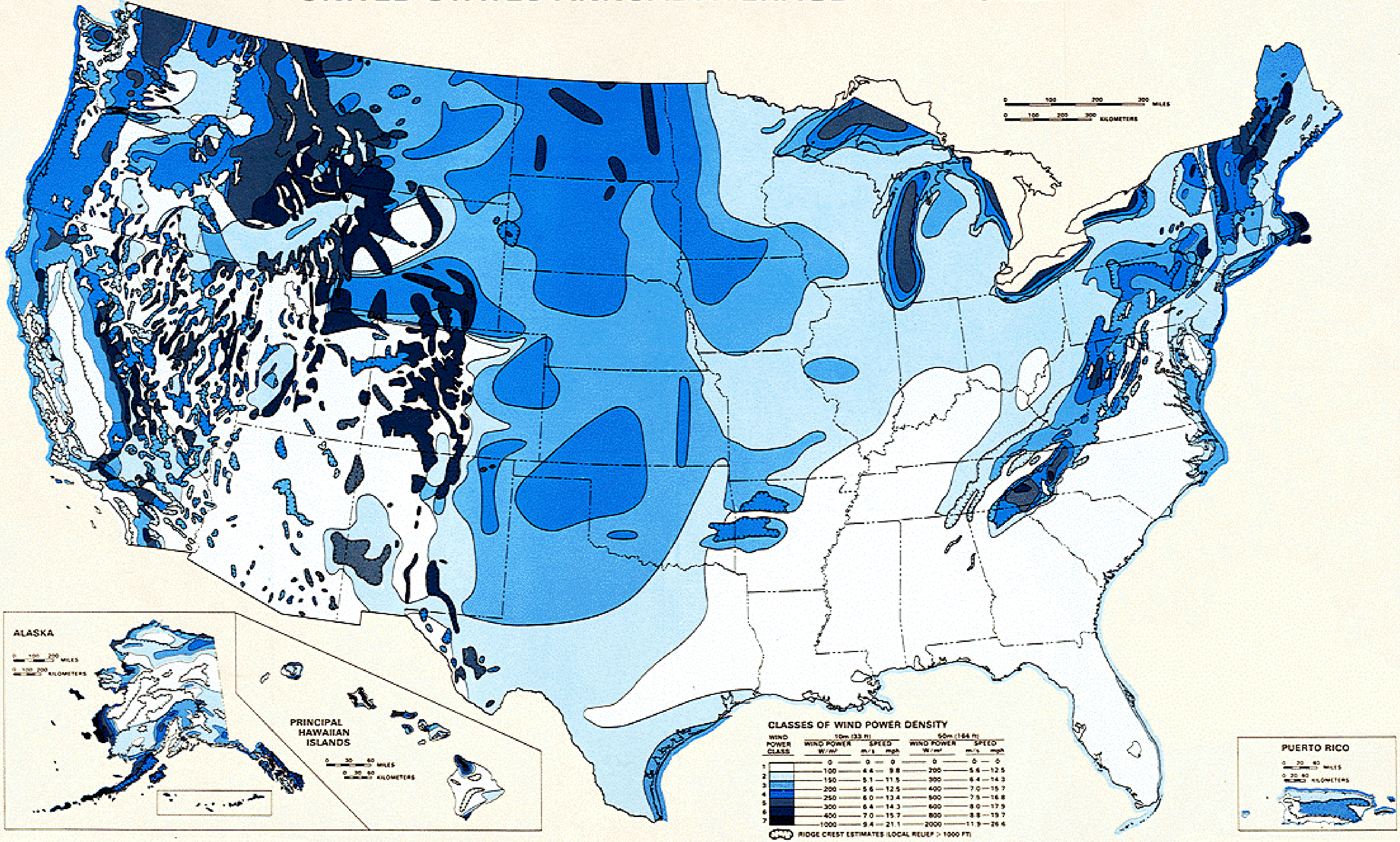
Early 1990s

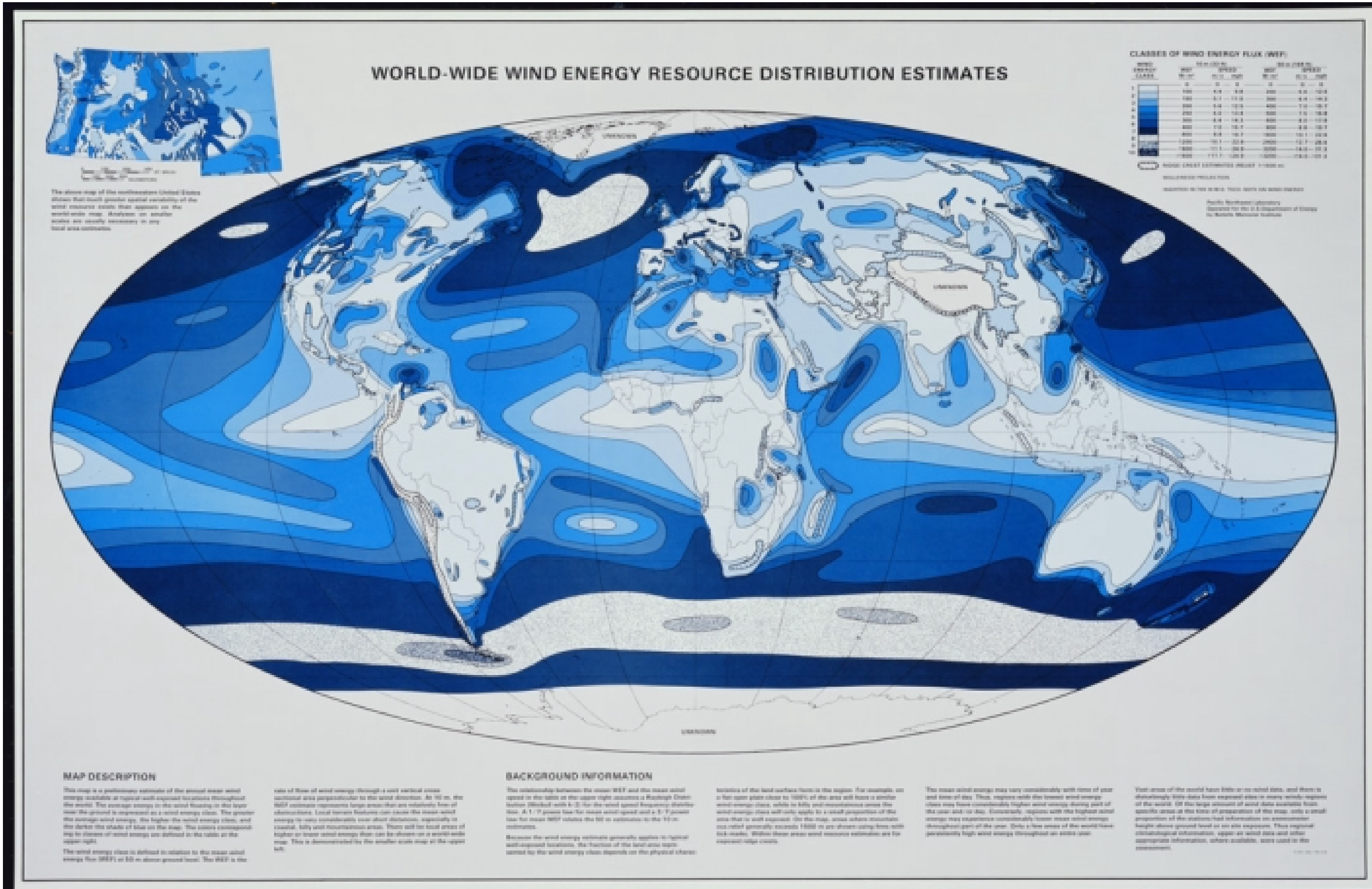
- **New global meteorological data sets offer potential for improved wind assessments (e.g., Mexico, Indonesia)**
- **New digital geographic data sets facilitate GIS-based mapping (e.g., Digital Chart of the World)**

Late 1990s

- **Development of NREL's GIS-based wind mapping system**
- **Improvements in data analysis and assessment techniques**
- **Wind mapping applications in diverse regions of the world**
- **Validation of mapping results**

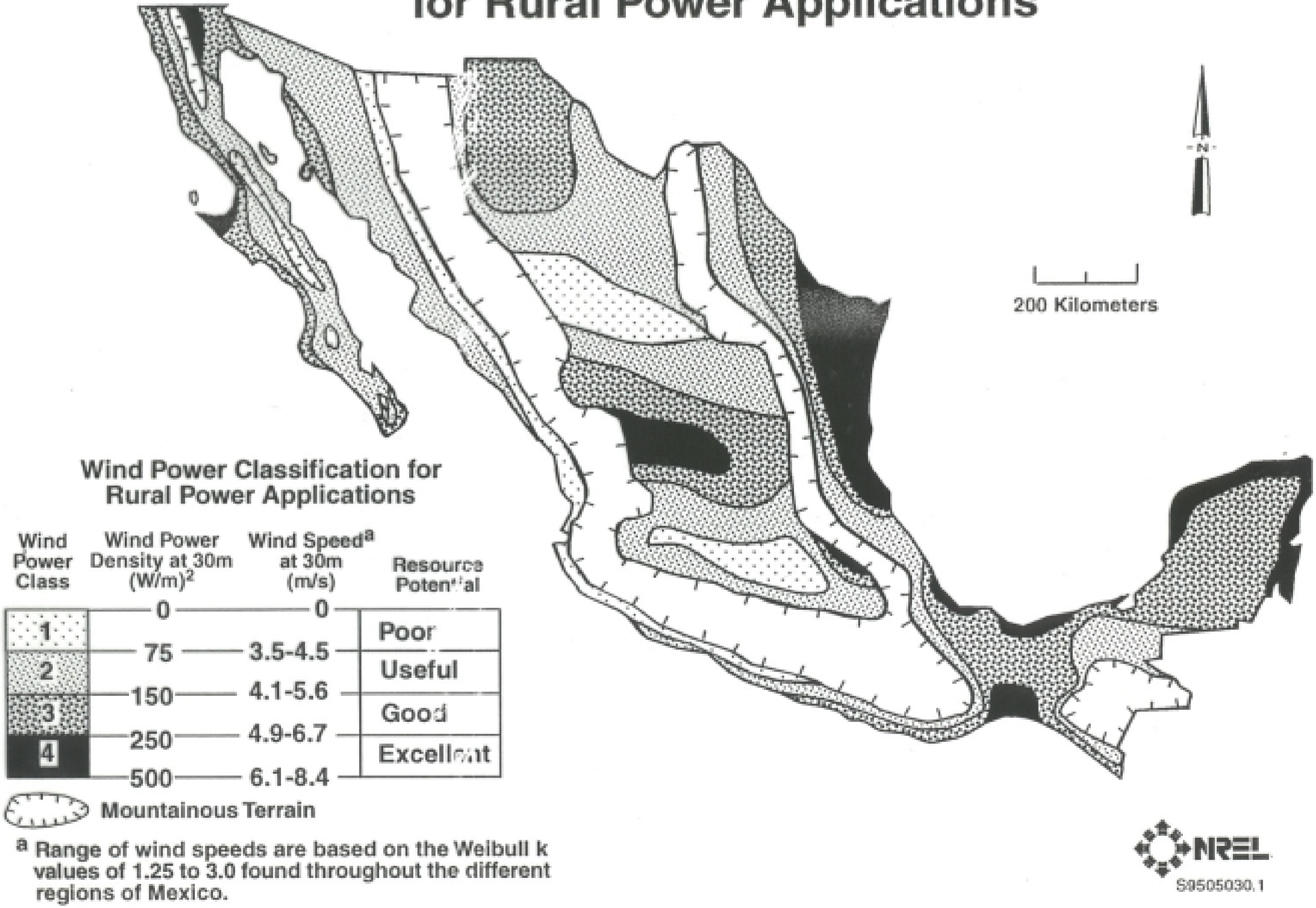
UNITED STATES ANNUAL AVERAGE WIND POWER





WORLD-WIDE WIND ENERGY RESOURCE DISTRIBUTION ESTIMATES
CLASSES OF WIND ENERGY FLUX (WEF)
UNKNOWN
MAP DESCRIPTION
BACKGROUND INFORMATION

Mexico - Preliminary Wind Resource Map for Rural Power Applications



Future Developments of NREL Wind Mapping System

- Perform additional validation studies
- Incorporate new climatic and land use data sets into mapping system
- Develop more sophisticated atmospheric mixing algorithms
- Explore new tools for advanced versions (e.g., mesoscale numerical models)

Program Accomplishments

Unique world-class capability in wind resource assessment and mapping established at NREL through development and application of:

- Global data bases and analysis tools for producing reliable wind assessments, essentially anywhere in the world
- Sophisticated GIS-based mapping system for producing large-area high-resolution (1-km) wind maps